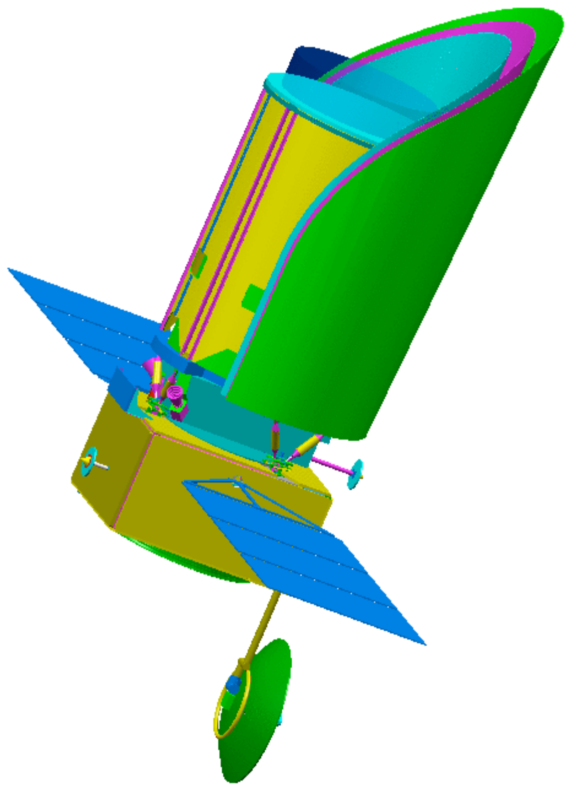
ACCESS -- a science and engineering assessment of space coronagraph concepts for the direct imaging and spectroscopy of exoplanetary systems



John Trauger (Jet Propulsion Laboratory / Caltech)

Meeting of the American Astronomical Society
Long Beach -- 8 January 2009

ACCESS Science and Engineering Team

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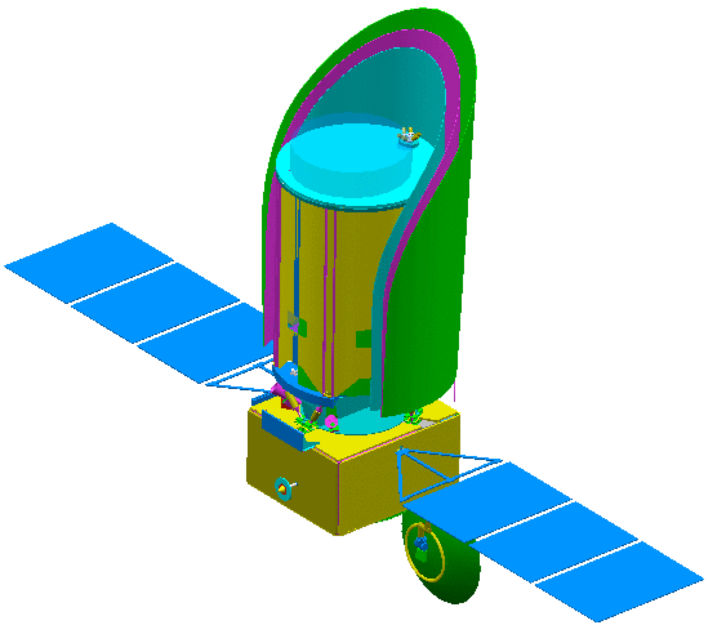
ACCESS
Actively-Corrected Coronagraphs for Exoplanetary System Studies



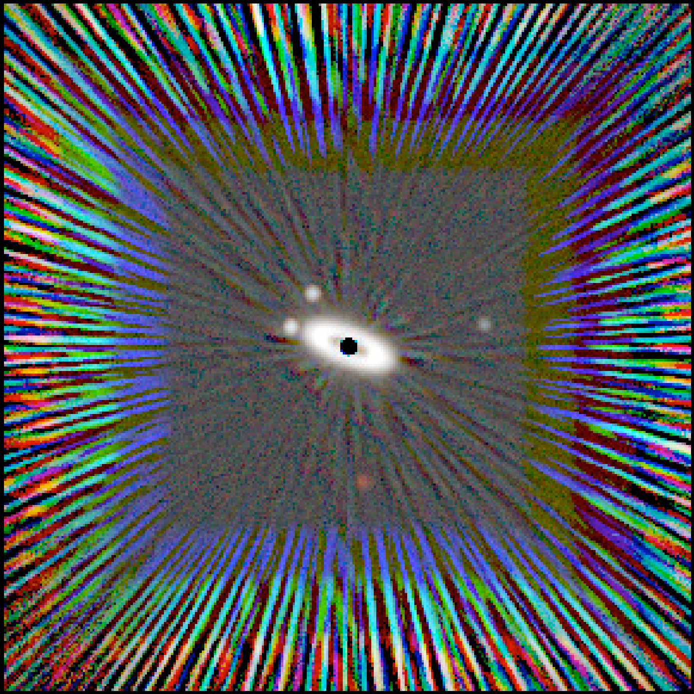
- Overview
- Science objectives
- Study objectives
- Coronagraph types
- Metrics
- ACCESS observatory
- Laboratory validations
- Summary

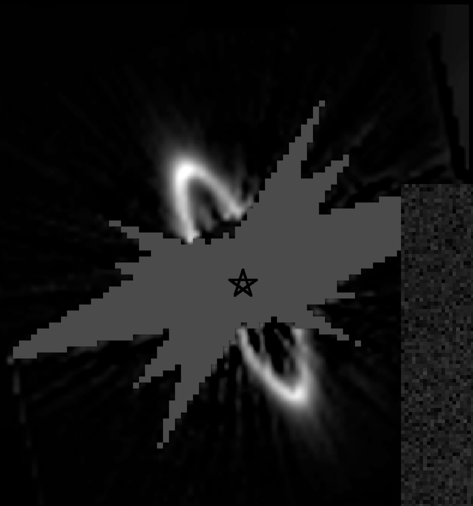
ACCESS Overview

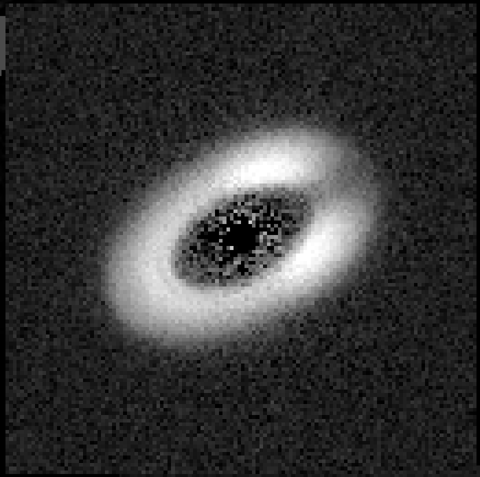
- *ACCESS is one of four medium-class exoplanet concepts selected by NASA for ASMCS studies ($600M + launch vehicle)*
- *Coronagraphic imaging and spectroscopy of exoplanetary systems at visible wavelengths (450-900 nm)*
- *Study compares performance and readiness of four major coronagraph architectures*
- *Defines a conceptual space observatory platform as the "level playing field" for comparisons among coronagraph types*
- *Also uses laboratory validation on JPL's HCIT as another "level playing field" for coronagraph hardware readiness*
- *Evaluates science reach of a probe-class coronagraph mission*
- *Goal is to identify one or more capable mission concepts at TRL6+*

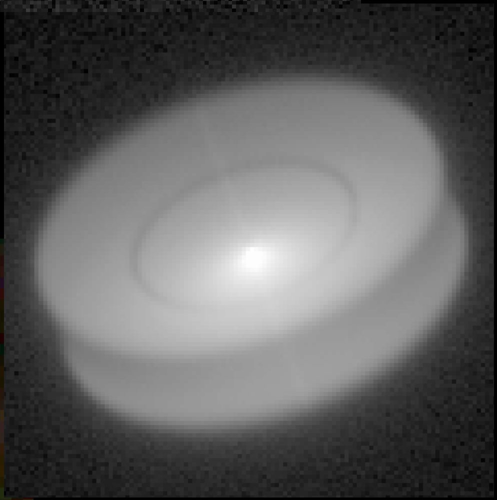
ACCESS science objectives

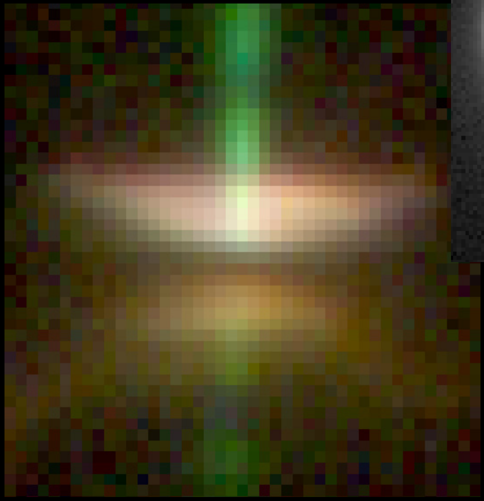
- *Direct coronagraphic imaging and low-resolution spectroscopy of exoplanet systems in reflected starlight, to include:*
- *Census of nearby known RV planets in orbits beyond ~1AU*
- *Search for mature exoplanet systems beyond the RV survey limits, including giant planets, super-earths, and possibly a dozen earth-mass planets*
- *Life cycle of planetary systems: "dust-to-dust" in the circumstellar environment*
- *Zodi structure as an indicator of unseen planets and planetesimals*
- *Zodi dust as a critical architecture issue for future large missions for exoplanet detection and characterization*











The space coronagraph provides high-contrast imaging and spectroscopy of mature exoplanet systems, as well as the evolution and "dust-to-dust" life cycle of planetary systems.

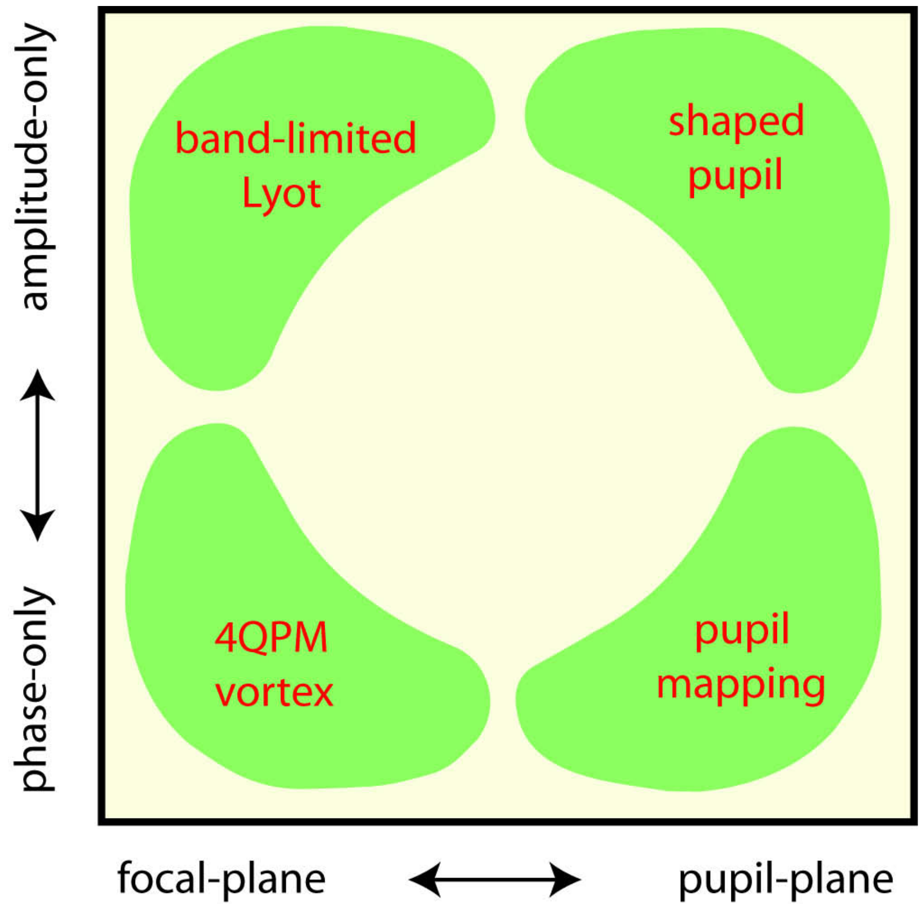
ACCESS engineering approach

- *We seek an observatory architecture representative of the "best" available for exoplanet coronagraphy within the scope (cost, risk, schedule) of a NASA medium-class mission*
  - *single spacecraft*
  - *visible wavelengths (500-900 nm)*
- *In particular, all coronagraphs require an observatory system with*
  - *active wavefront control*
  - *exceptional pointing control and*
  - *exceptional wavefront stability*
- *We seek systems with high technology readiness (TRL6+) for*
  - *reliable estimates of science capabilities and*
  - *reliable determinations of cost and schedule*
- *Baseline observatory architecture defines a capable platform for fair comparisons among coronagraph types.*

ACCESS gamut of coronagraph types

Moody,
Trauger,
Traub
C = 1e-9
(3-10 lambda/D)
10% bandwidth

Belikov, Pueyo,
Vanderbei,
Kasdin, Spergel
C = 2e-9
(4-10 lambda/D)
10% bandwidth



Mawet,
Serabyn,
Schneider
C = 1e-5
(2 lambda/D)
7.5% bandwidth

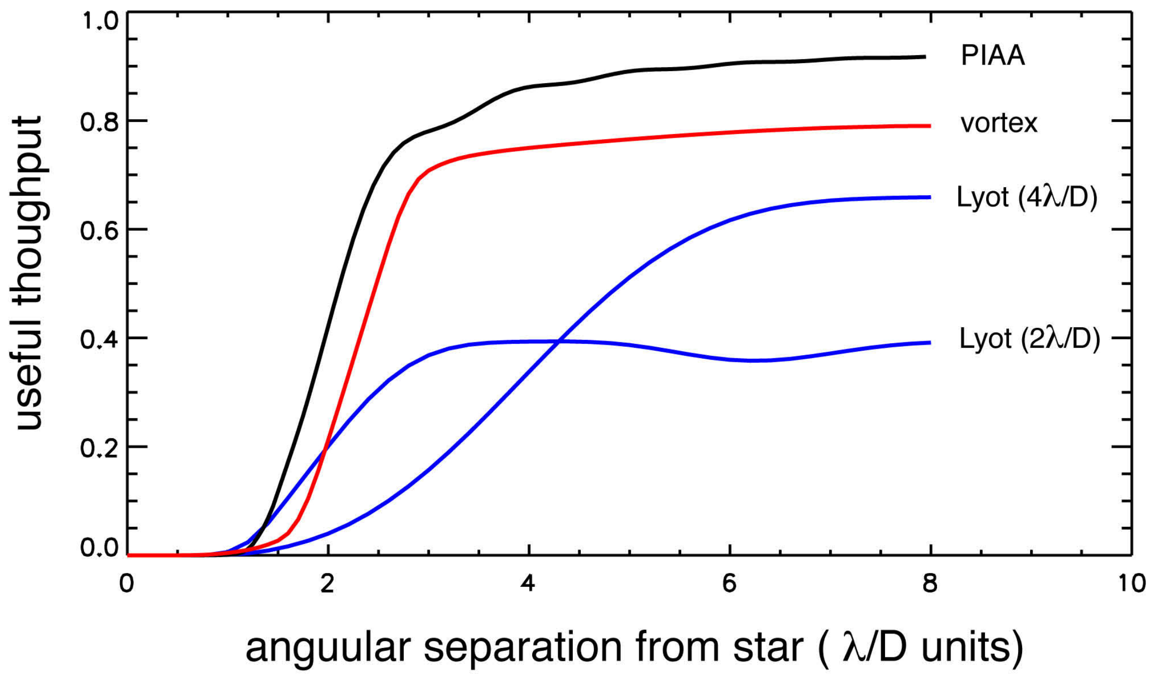
Guyon,
Belikov,
Vanderbei
C = 7e-7
(2-4 lambda/D)
monochromatic

(C = best demonstrated contrast to date)

Coronagraph metrics

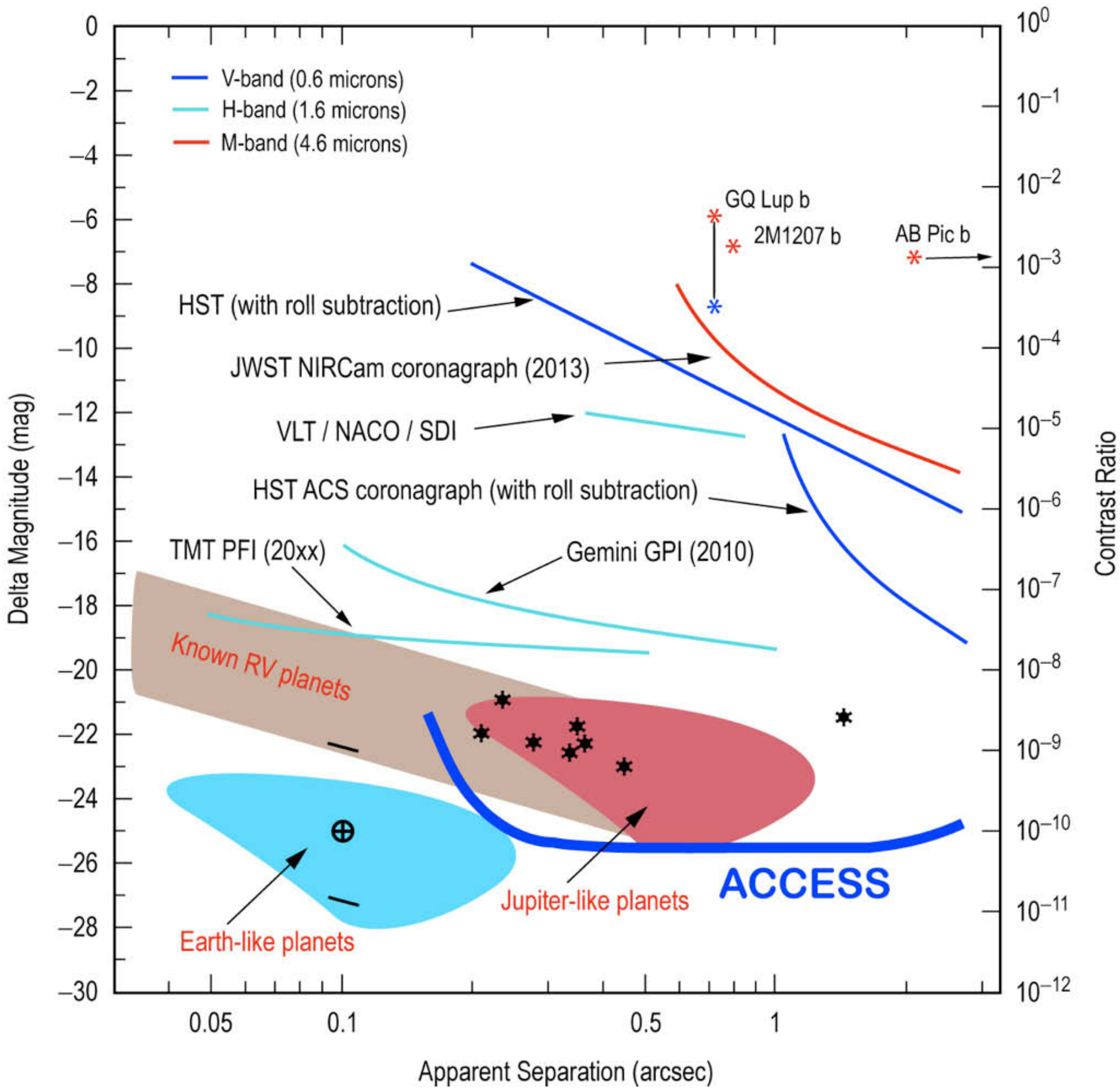
- *Performance predictions for the science reference mission*
  - *High contrast*
  - *Small inner working angles*
  - *High S/N and throughput efficiency*
  - *Science mission simulations and assessment*
- *Technology readiness for the science reference mission*
  - *High contrast as demonstrated in the laboratory*
  - *Assessment of current technologies*
- *Complexity and cost*

Coronagraph metrics

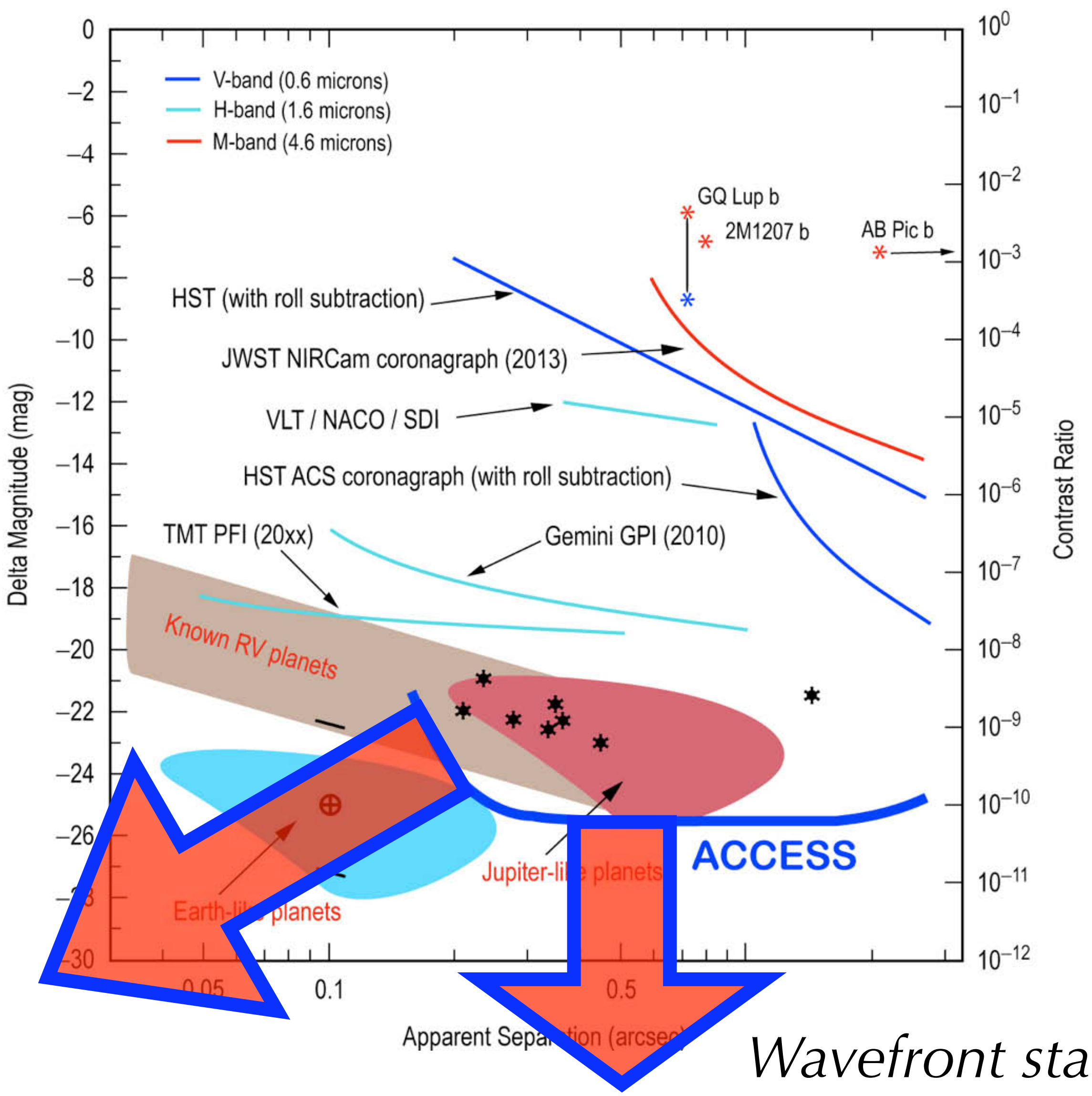


- *A variety of coronagraph types can in principle work with 1e-10 contrast and inner working angles as small as 2 lambda/D.*
- *ACCESS also examines other significant performance factors, including PSF shapes, instrument complexity, optical tolerances, and any others that affect the coronagraph performance in practice.*

ACCESS Discovery Space



ACCESS Discovery Space with improved pointing control and wavefront stability

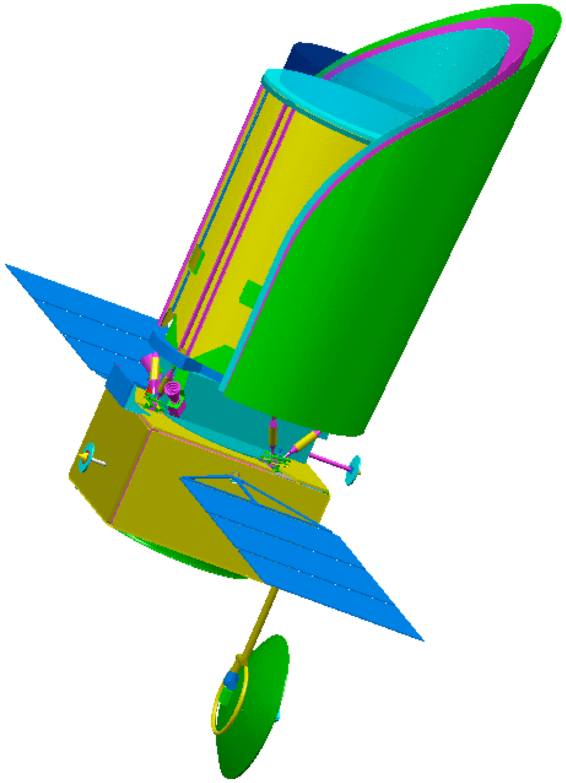


Pointing control and low-order wavefront stability

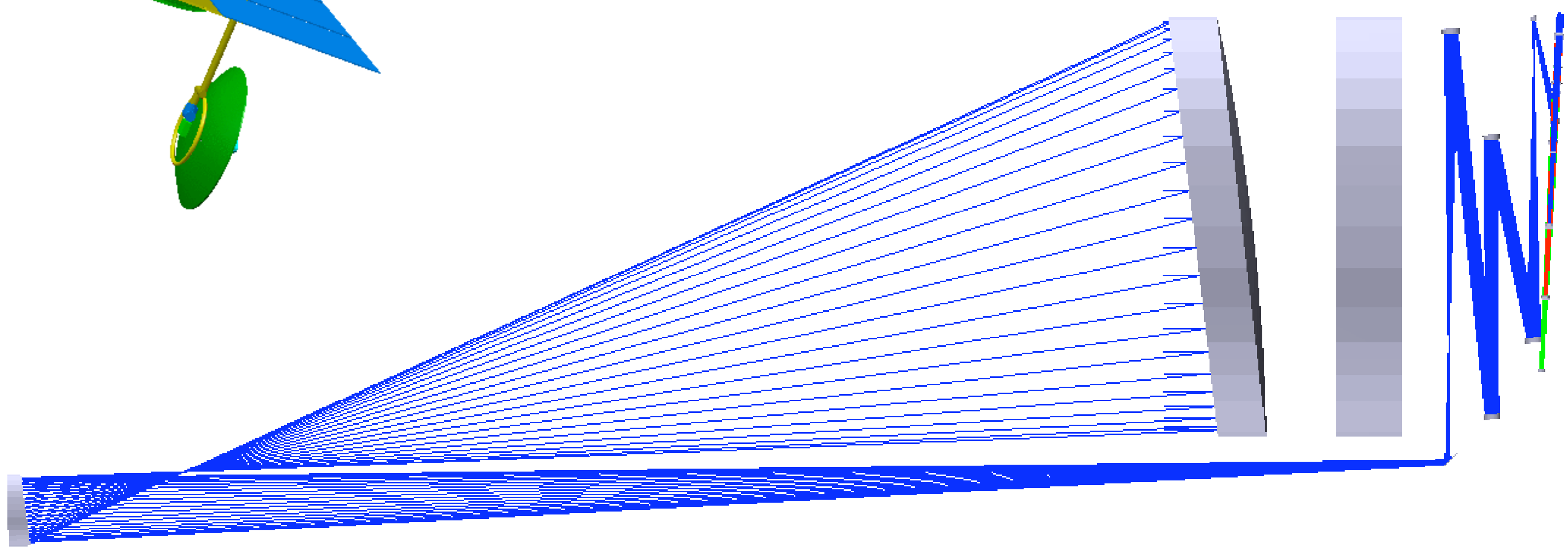
Wavefront stability

Observatory provides the "level playing field"

- *Telescope -- 1.5 meter, unobscured off-axis, gregorian, stable metering structure, thermal control system.*
- *Spacecraft -- NGC T310 configured for L2 orbit, thermal shield*
- *Pointing control system -- end-to-end system design including telescope and spacecraft dynamics, active vibration damping, and pointing knowledge and fine correction provided within the coronagraph*
- *Active wavefront control, sensing and control algorithms*
- *Wavefront stability -- end-to-end design of the thermal control system*
- *Focal plane imaging and integral field spectroscopy*
- *End-to-end coronagraph computational models for sensitivity analysis and tolerancing*
- *As much as possible, the same computational techniques are applied to all coronagraph types for evaluation of the ACCESS science reference mission*



ACCESS observatory:
1.5 meter -
unobscured off-axis -
gregorian telescope

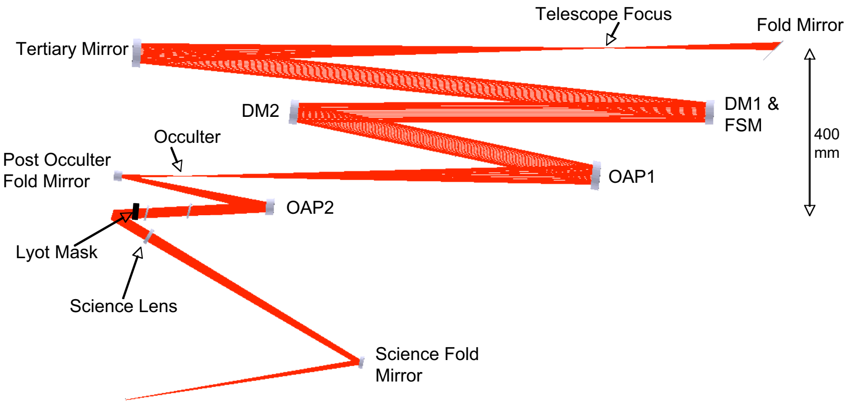


Coronagraph optical layout

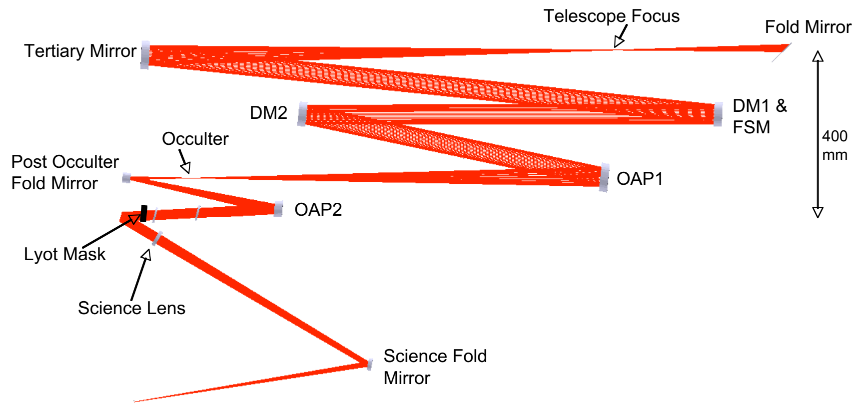
- *Coronagraph "front end" is identical for all four ACCESS coronagraph types: Telescope PM&SM, Fold, Tertiary, integrated DM1+Fine Steering Mirror, DM2, OAP1, i.e., all optical elements leading to the first instrument focal plane.*
- *All four coronagraphs can use the centration of the star image at this first instrument focal plane for the pointing knowledge required by the attitude control system (ACS).*
- *All four coronagraphs perform wavefront control with a pair of 48 mm diameter DMs, each DM with 1810 actuators driving a continuous mirror facesheet.*
- *Telescope PM and DM1+FSM are in conjugate planes.*
- *Science lens projects coronagraph image onto the science CCD*
- *Only the V-band (500-600 nm) channel is shown (next slide).*

The four coronagraph optical layouts

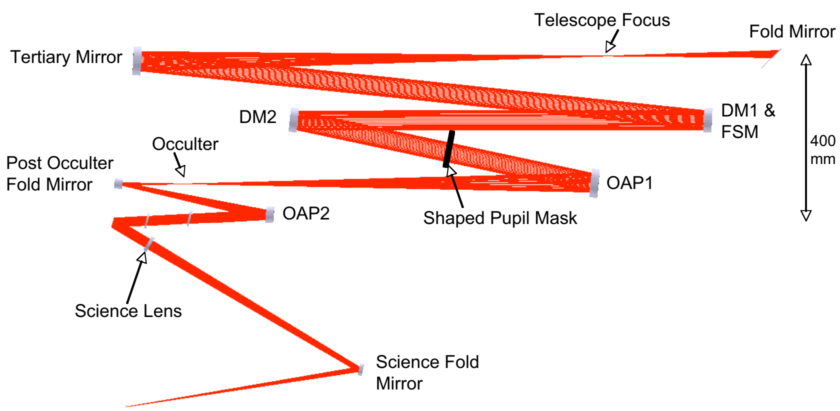
Lyot coronagraph



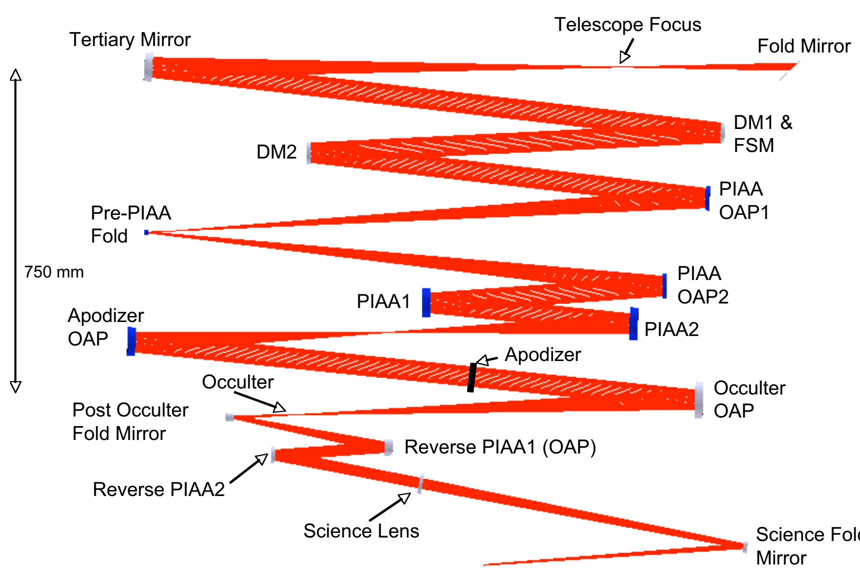
Vortex coronagraph



Shaped pupil coronagraph

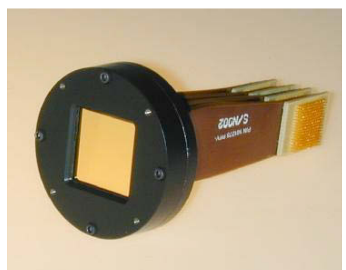


Pupil mapping coronagraph



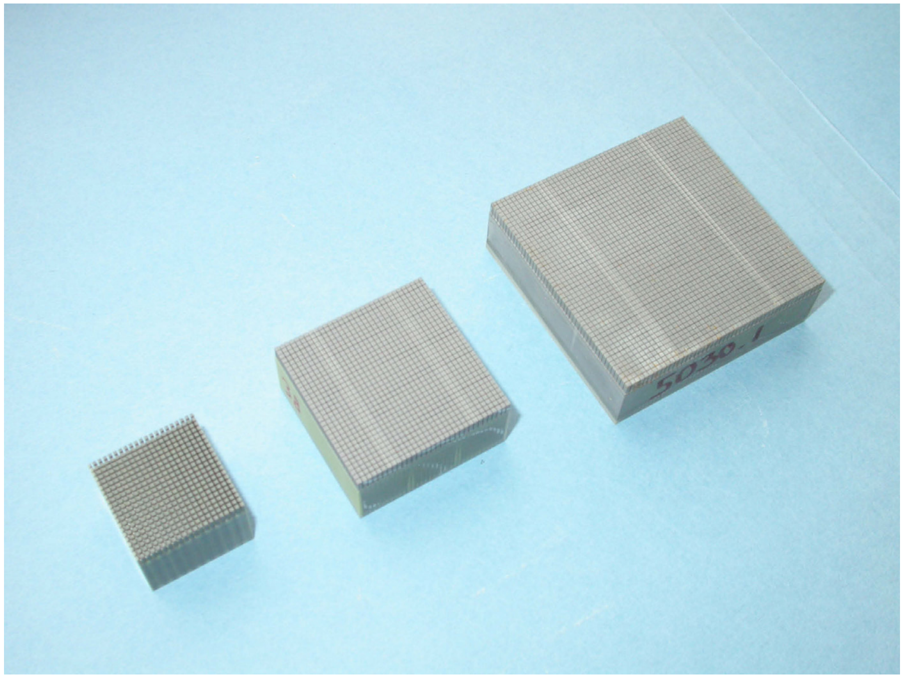
Wavefront control on the "level playing field"

- *Telescope and coronagraph use state-of-the-art optics and structures for diffraction-limited imaging*
- *Pointing control system and thermal control system stabilize the optical wavefront*
- *A pair of 48 mm diameter deformable mirrors (1810 actuators each) and wavefront sensing at the science focal plane provide the high-contrast dark field for planet detection and characterization.*

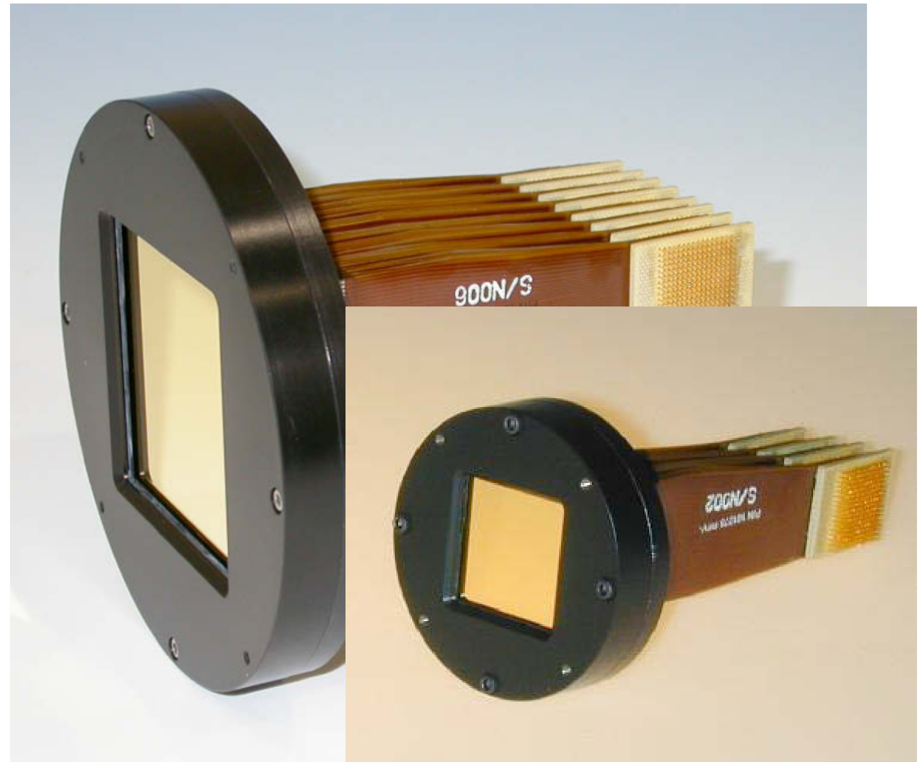


The DM technology for ACCESS has been demonstrated with 32x32 and 64x64 actuator arrays. Mirror surface is polished to λ/100 rms. Surface figure is stable (open loop) to 0.01 nm rms. Together with wavefront sensing and control algorithms that require only images at the coronagraph focal plane, this DM technology has demonstrated stable contrast at the 5e-10 level in the laboratory.

Deformable mirror development for HCIT



Evolution of monolithic PMN actuator arrays by Xinetics: 21x21, 32x32, and 48x48 arrays. A fused silica facesheet is bonded to the actuator array (top side). Electrical connections (on the bottom side) complete the DM.

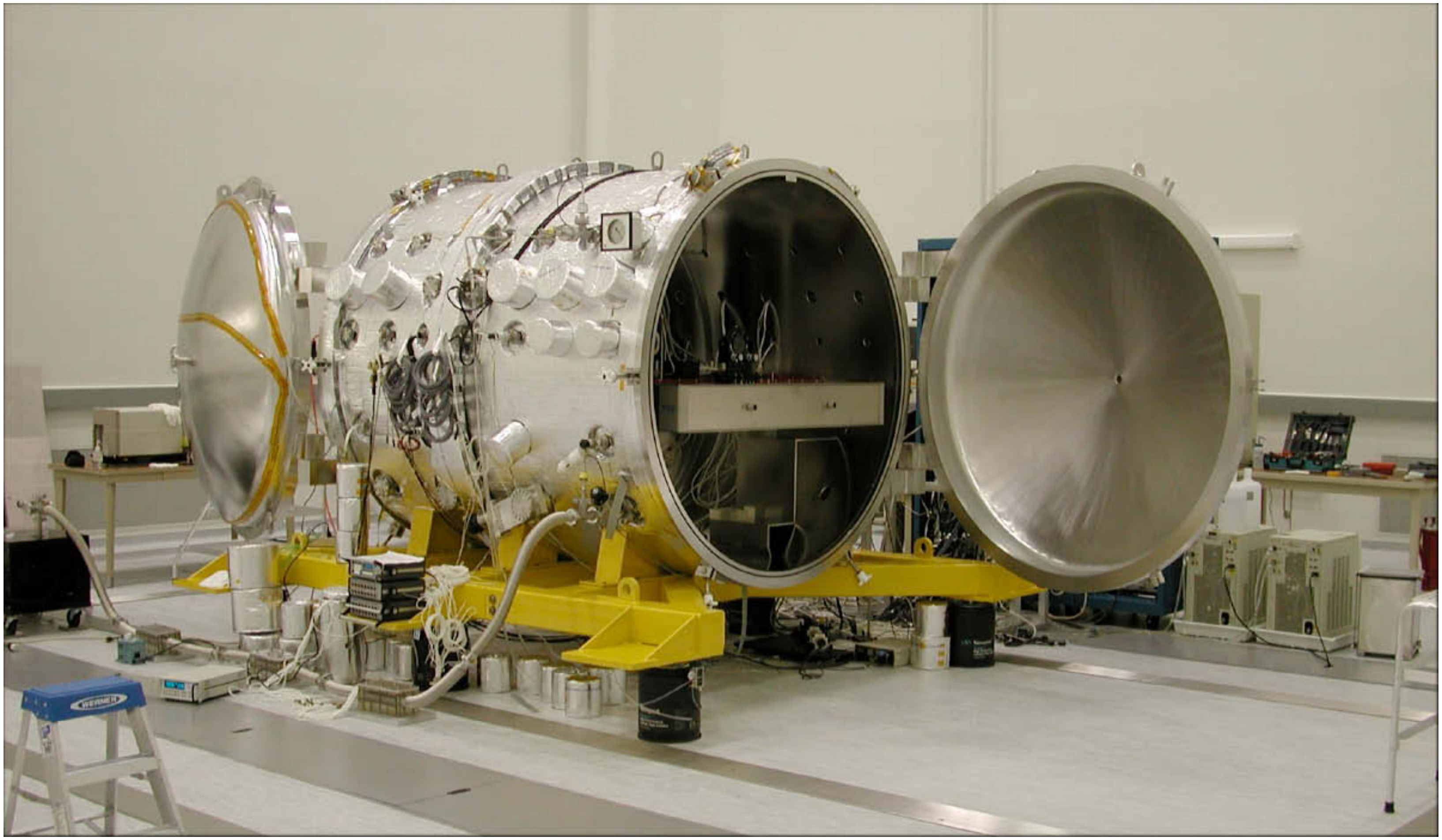


DMs delivered to JPL by Xinetics. Larger arrays are formed by bonding modules together: here a 64x64 array is built up with four 32x32 modules. Mirror surface is polished to $\lambda/100$ rms. Surface figure (open loop) is stable to 0.01 nm rms.

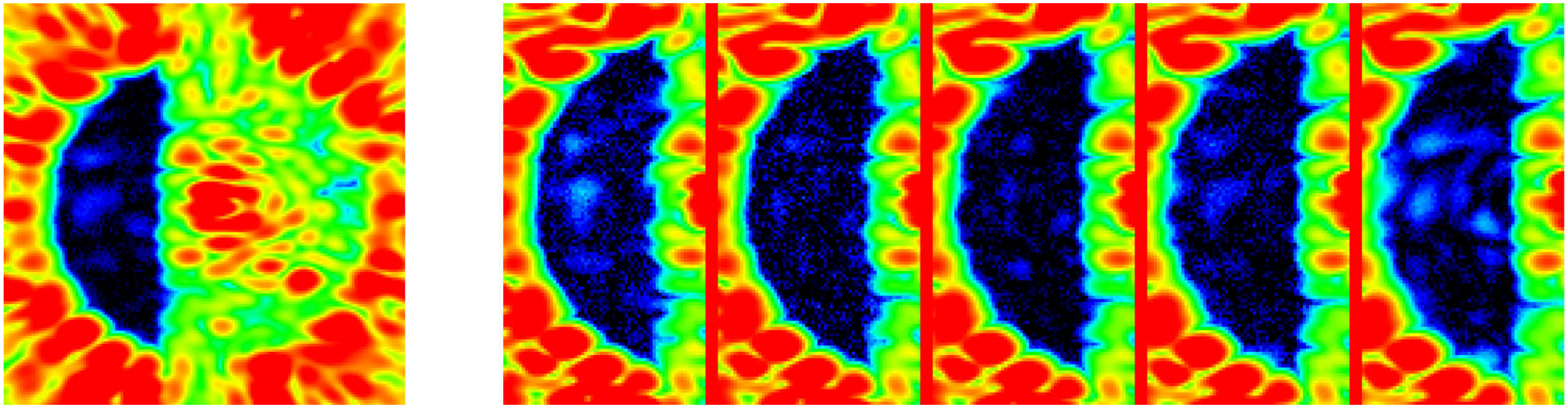
Laboratory testbed demonstrations

- *Laboratory testbed demonstrations provide another "level playing field" for evaluating the readiness of coronagraph hardware and algorithms*
- *Although hardware development is not covered by the ASMCS studies, we have an opportunity to validate relevant technologies in focused laboratory experiments during the study year*
- *Experiments are in progress on the High Contrast Imaging Testbed (HCIT) at JPL, supporting both PECO (Olivier Guyon, PI) and ACCESS during the year of ASMCS studies*
- *Laboratory activity for the four ACCESS coronagraph types are as follows.*

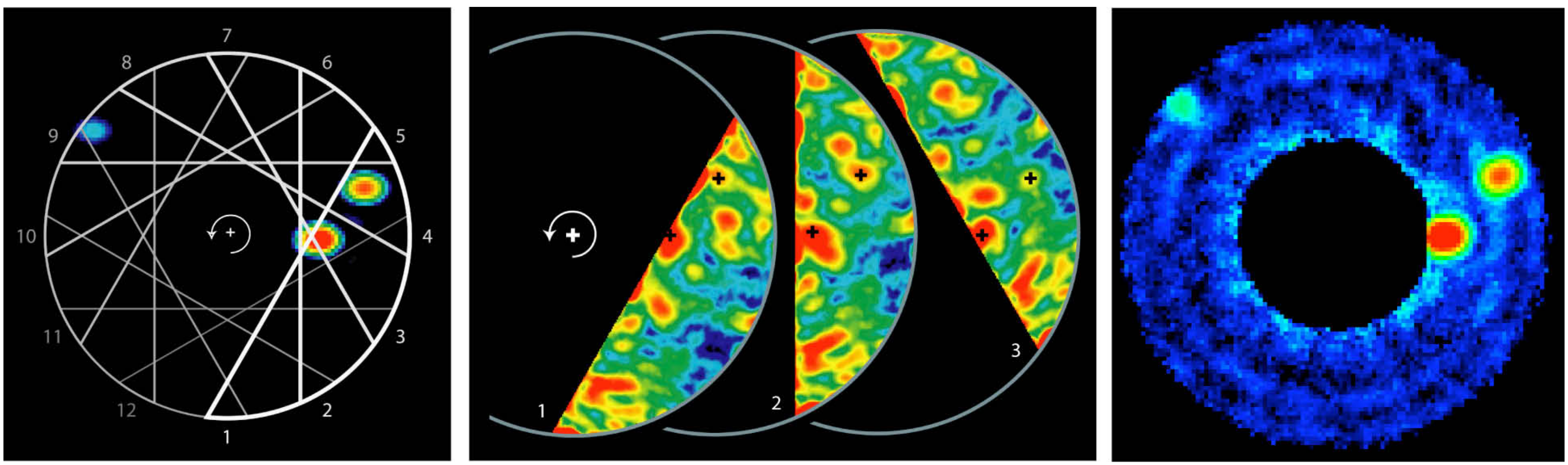
High Contrast Imaging Testbed at JPL



High Contrast Imaging with the HCIT

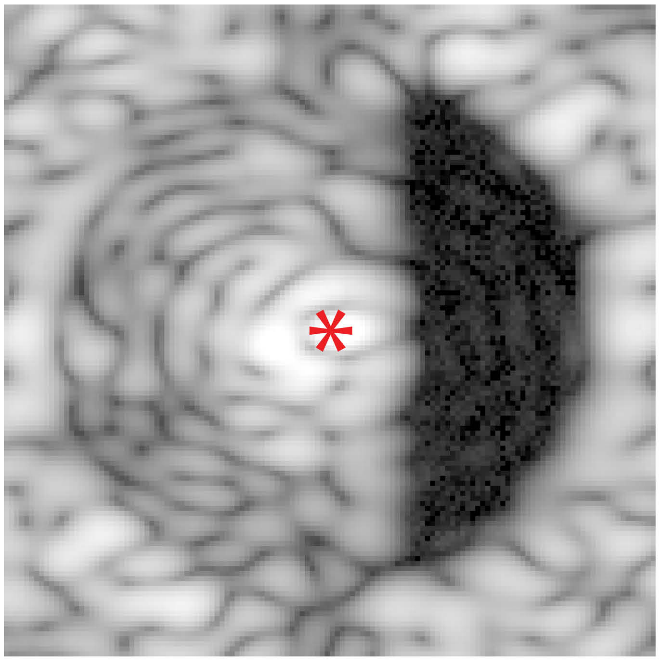


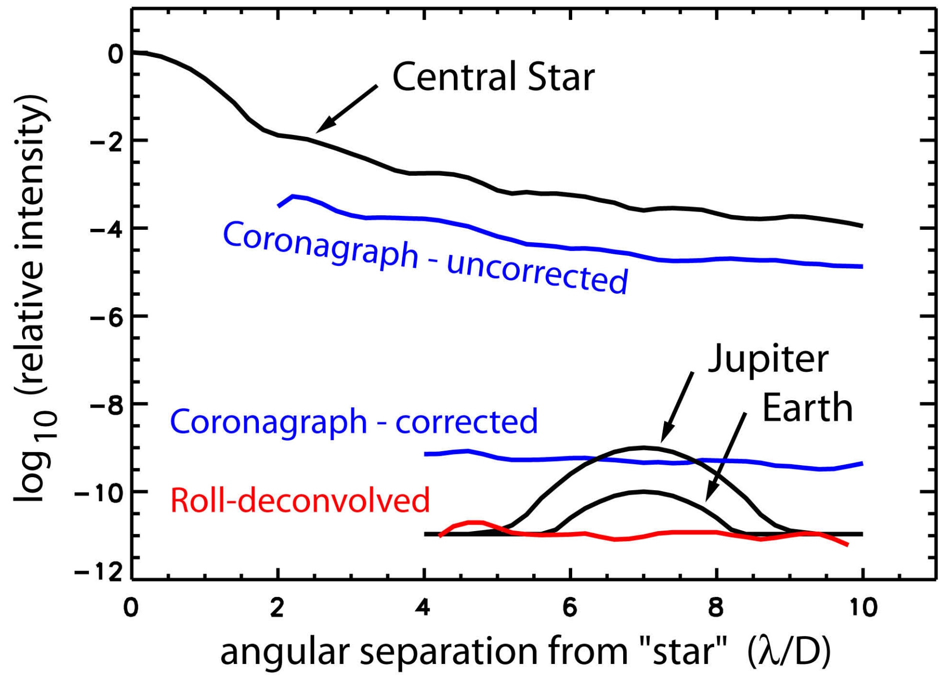
Laboratory demonstrations of high-contrast coronagraph dark fields, with starlight suppressed to levels beyond billion-to-one (2008).



Simulations of coronagraph data processing, using laboratory data, demonstrate one method to distinguish Earth-like planets from the glare of the central star.

Laboratory coronagraph contrast and stability

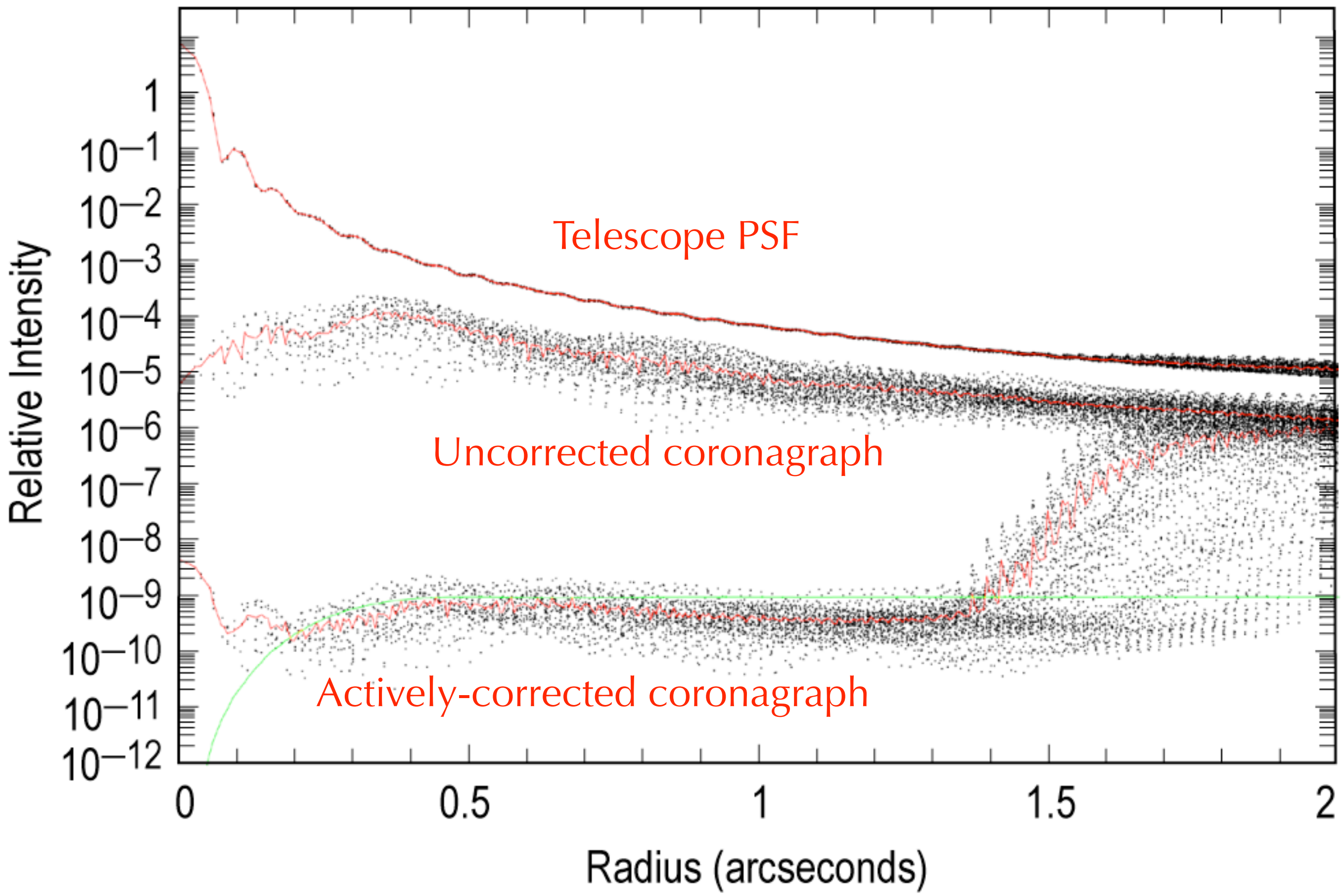




Comparison of azimuthally averaged PSFs of (a) the star, with focal plane mask offset and Lyot stop in place; (b) the coronagraph field with all DM actuators set to equal voltages; (c) the coronagraph with DM set for a dark half-field; and (d) the result of simulated roll deconvolution with the set of 480 consecutive coronagraph images. PSFs of a nominal Earth and Jupiter are also indicated.

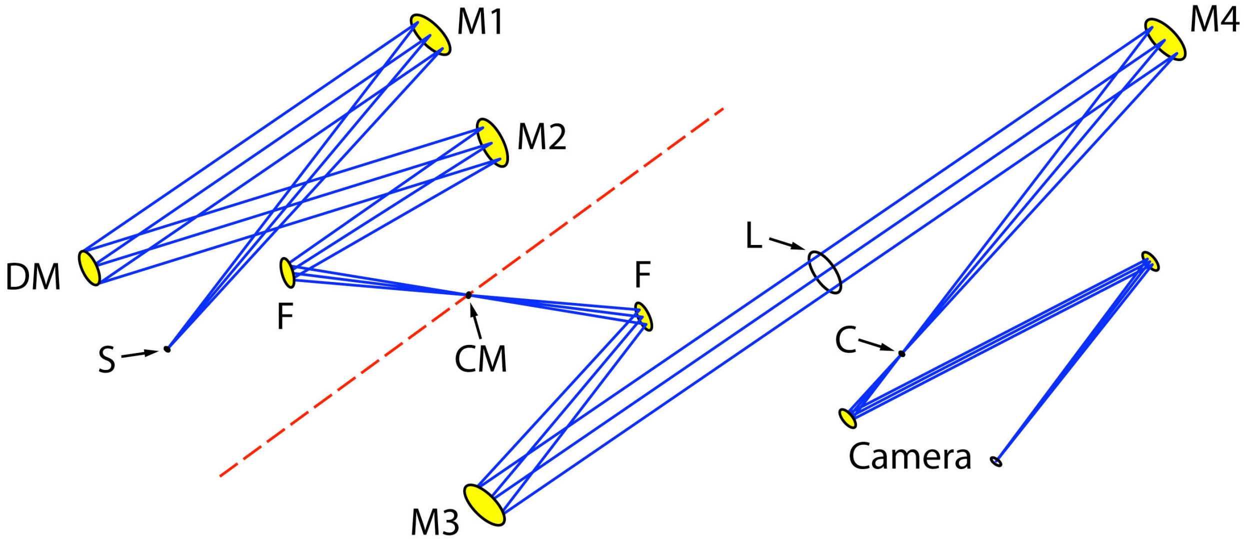
(Trauger & Traub, *Nature*, 12 April 2007, p771)

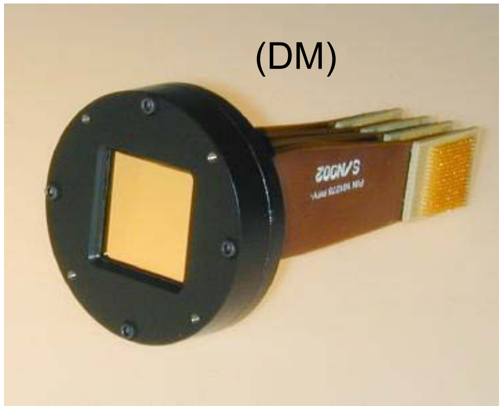
Experiments validate models; models provide performance predictions: V-band imaging with a space coronagraph



Plotted are the point spread functions (PSFs) of a 1.8 meter telescope, coronagraph, and coronagraph with active wavefront correction. Instrument contrast is better than 1e-9 with an inner working angle of 0.25 arcsec for broadband (20%) visible light.

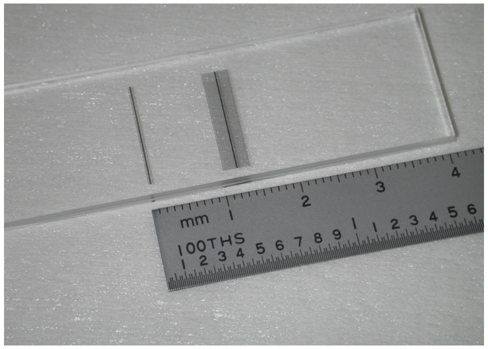
HCIT coronagraph optical layout





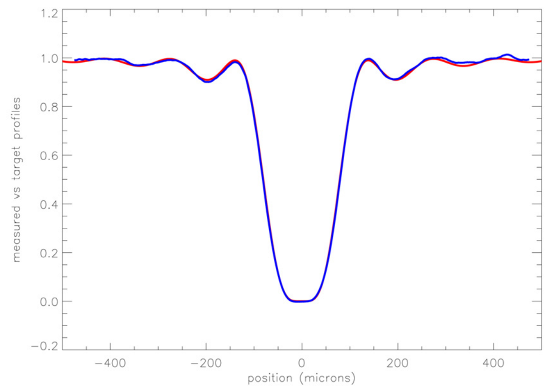
- "Star" is a pinhole illuminated by a supercontinuum light source + interference filters
- Off-the-shelf lambda/20 mirrors
- f/25.8 beam illuminates the coronagraph mask (CM)
- Single 32x32 DM, low-power MUX driver
- Coronagraph image is magnified x3 at science CCD to ~4.5 pixels / airy
- Optical table enclosed in a thermally-isolated, vibration-damped vacuum chamber.

Lyot coronagraph on the HCIT



THICKNESS-PROFILED NICKEL MASK

Nickel mask has been vacuum-deposited on a fused silica substrate. Attenuation profile was built up in a number of passes with a computer-controlled moving slit. The same mechanism will be used to superimpose a dielectric phase layer in future work.



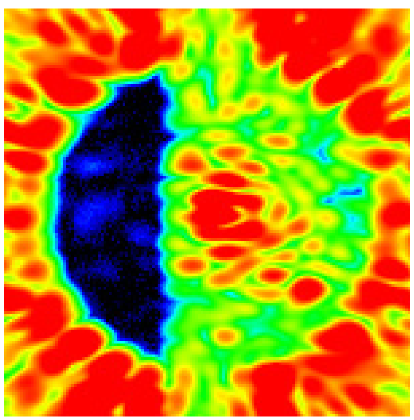
Comparison of the prescribed transmittance profile with the measured profile of the mask pictured at left. Desired profile is the red curve, the measured profile is the blue curve.

Recent contrast measurement on the HCIT:

6.4×10^{-10}

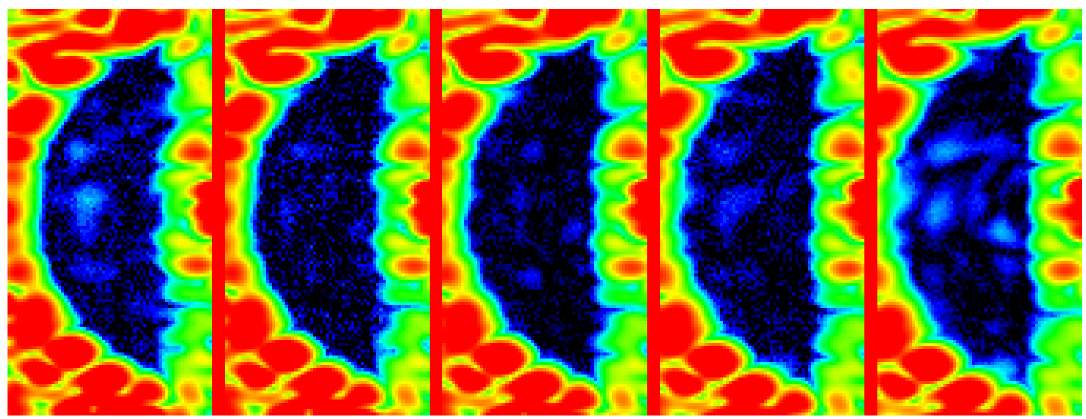
in 10% bandwidth light (over the entire 4-10 lambda/D dark field, and also over the inner 4-5 lambda/D area).

LABORATORY CORONAGRAPH HIGH-CONTRAST IMAGES



760-840 nm

Laboratory demonstration of Lyot coronagraph contrast averaging 6.4e-10 across a 760-840 nm (10%) spectral bandwidth. The dark field extends from a vertical line offset 4 λ/D left of the occulted "star" to an outer radius at 10 λ/D centered on the "star".



760-778 nm | 778-792 nm | 792-808 nm | 808-824 nm | 824-840 nm

Contrast images in five contiguous 2% passbands shows the evolution of the background speckle field of speckles across the 10% bandwidth image at left. Contrasts measured over the entire 4-10 λ/D dark field average
7.5e-10, 7.8e-10, 7.2e-10, 6.2e-10, and 8.1e-10
in the five passbands respectively. Contrasts measured in the inner 4-10 λ/D dark field are respectively
5.4e-10, 7.2e-10, 8.9e-10, 8.2e-10, and 5.9e-10.

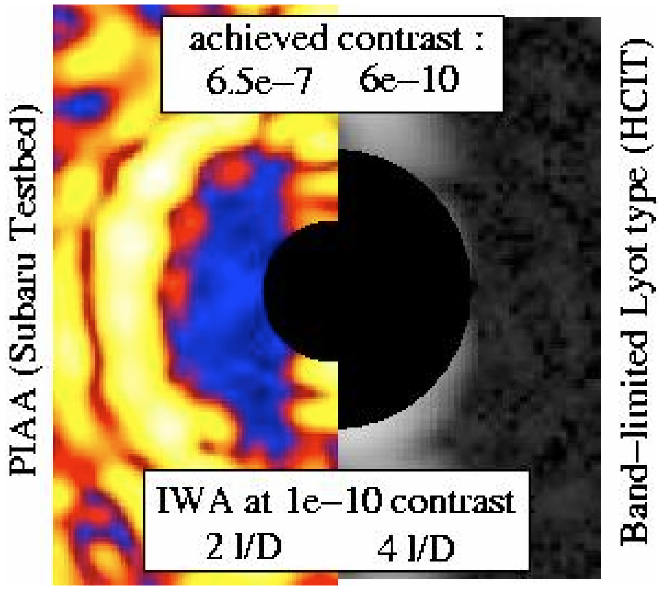
(Moody, Gordon, Trauger 2008)

Planned HCIT experiments with the hybrid-mask Lyot coronagraph

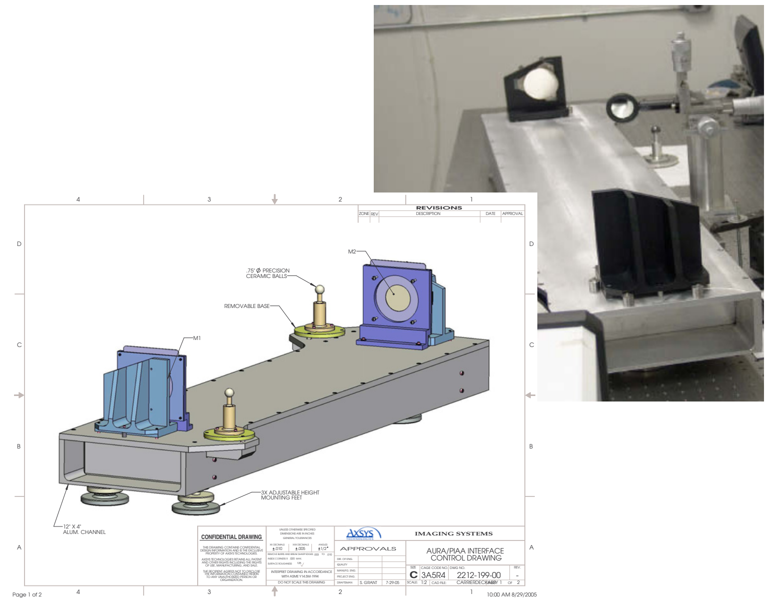
	Mask Configuration	Inner Working Angle	Spectral Bandwidth	Inner Contrast (x 10 $^{-10}$)	Outer Contrast (x 10 $^{-10}$)	ε	Lyot Throughput	
	nickel 4th-order	4 λ/D	10%	1.3 (4 - 5 λ/D)	1.4 (4 - 10 λ/D)	0.36	55%	
	hybrid 4th-order	4 λ/D	20%	2.1 (4 - 5 λ/D)	3.1 (4 - 10 λ/D)	0.26	67%	
	hybrid 4th-order	3.5 λ/D	20%	4.5 (3.5 - 4.5 λ/D)	4.5 (3.5 - 10 λ/D)	0.30	63%	
*	hybrid 4th-order	3 λ/D	20%	4.9 (3 - 4 λ/D)	5.0 (3 - 10 λ/D)	0.35	57%	*
	hybrid 4th-order	2.5 λ/D	20%	8.8 (2.5 - 3.5 λ/D)	8.2 (2.5 - 10 λ/D)	0.41	49%	

- *Achieved 1e-9 contrast in both 3-4 and 3-10 lambda/D fields with 10% spectral bandwidth using a 3 lambda/D nickel mask (summer 2008)*
- *Achieved 2e-9 contrast in both 3.5-4.5 and 3.5-10 lambda/D fields with 20% spectral bandwidth using a 3 lambda/D nickel mask (fall 2008)*
- *Contrast better than 1e-9 with inner working angles of 3 lambda/D over bandwidths of 20% are predicted for hybrid (metal + dielectric) masks, now beginning tests in the HCIT (autumn 2008)*

Pupil mapping (PIAA)

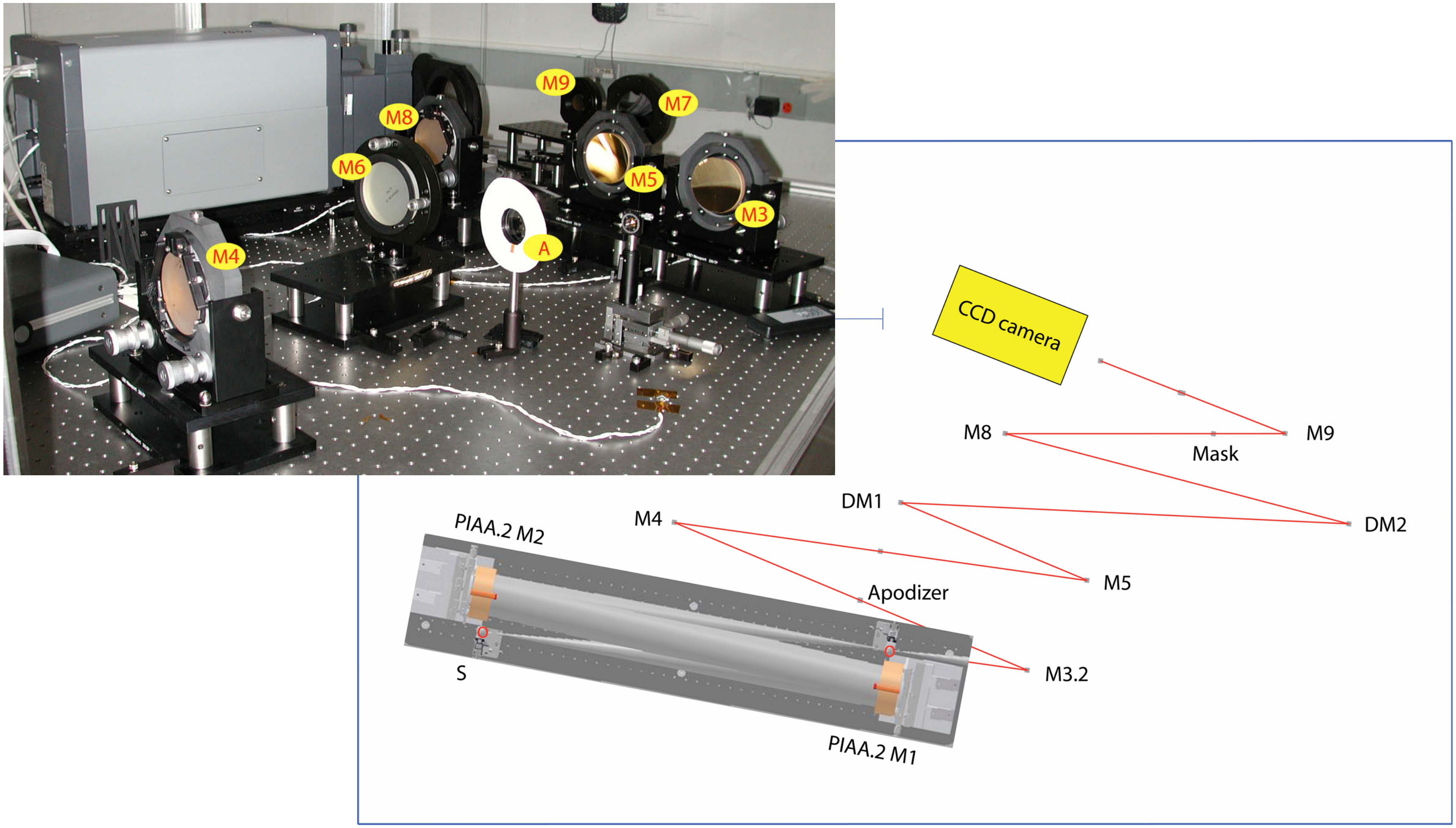


(Guyon 2006)



- *Pupil mapping approaches the theoretical maximum for coronagraph throughput.*
- *Has demonstrated 6.5x10-7 contrast at Subaru in monochromatic light (Guyon 2006)*
- *New PIAA system commissioned by NASA/Ames (Guyon, Belikov, Greene, McKelvey) is nearing completion at Tinsley, with delivery scheduled for 2008.*
- *Preparations are underway to test the new PIAA system on the HCIT upon delivery.*
- *NASA/Ames is currently testing earlier PIAA systems, and preparation of a new Ames testbed is underway.*

HCIT laboratory setup for PIAA demonstrations

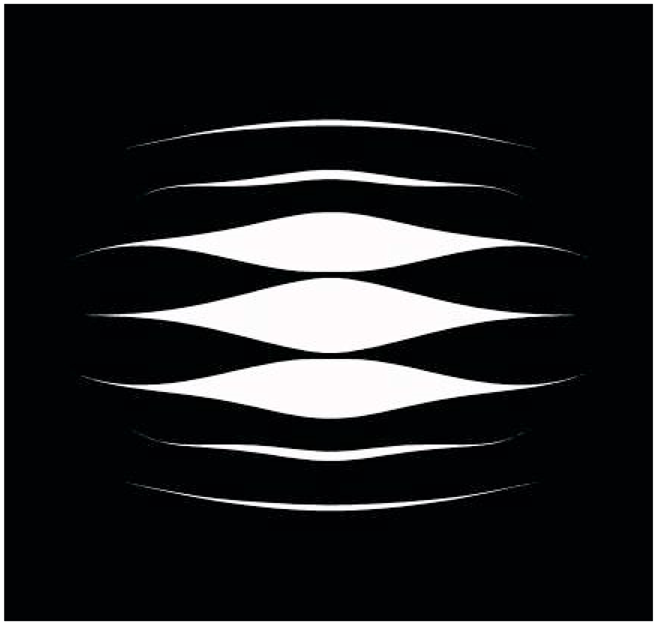


- *All optical components for the PIAA experiment are set up at JPL (June 2008).*
- *Tinsley will deliver PIAA system to NASA/Ames and JPL in late 2008, where it will be installed in the HCIT vacuum chamber for ASMCS experiments.*

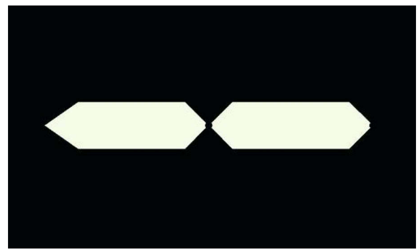
Shaped Pupils

- *The shaped pupil coronagraph has demonstrated 2.4e-9 contrast in 10% bandwidth on the HCIT.*
- *Integrated with a pair of DMs, inner working angles of 2.5 lambda/D for 1e-10 contrast and 17% efficiency is possible (Pueyo et al. 2007).*
- *Contrast of 1e-10 and throughput efficiencies of ~50% are possible with a narrowing of the dark field.*
- *Shaped (binary) pupil masks play a role in all coronagraph types.*

Shaped pupil coronagraph experiments with HCIT

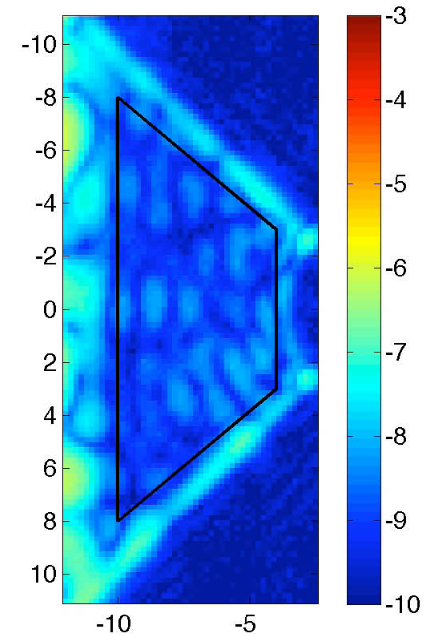


Shaped pupil mask



Focal plane mask

High contrast field



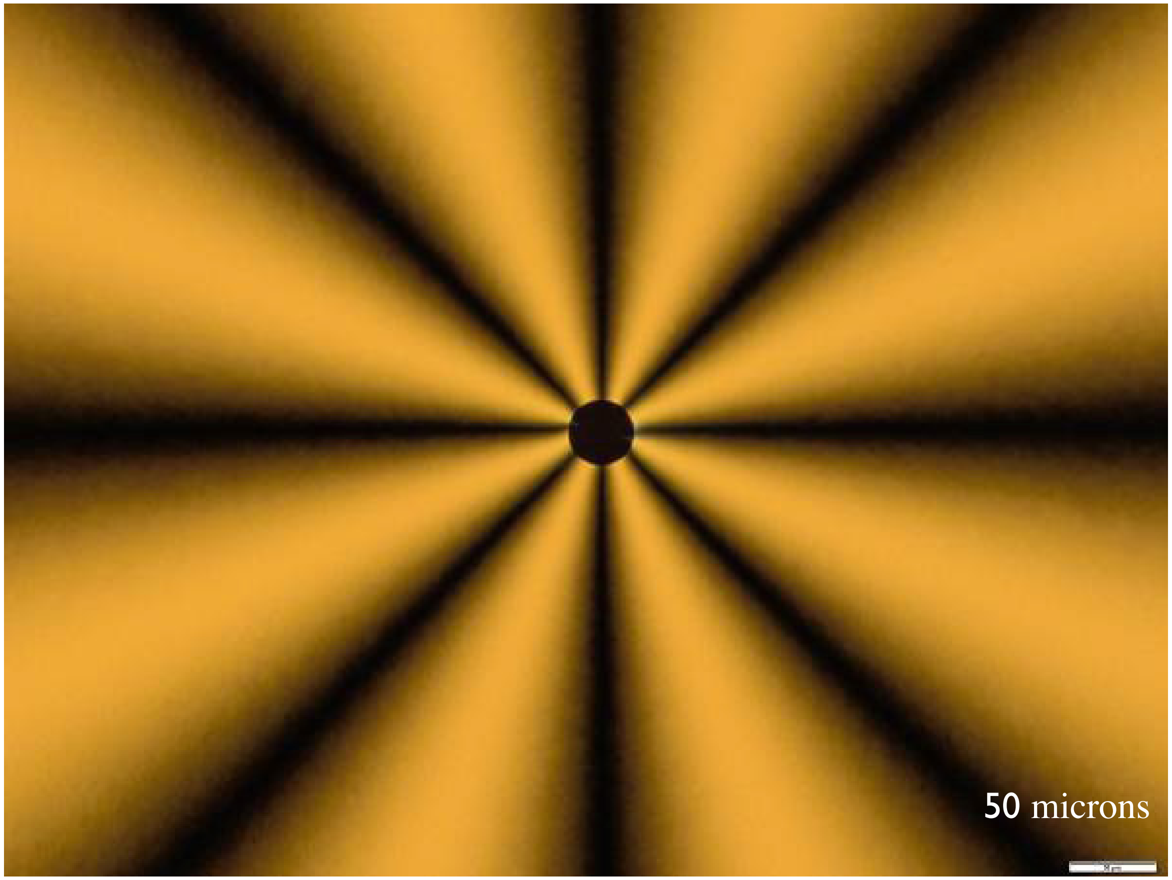
At left, the transmittance profile of a representative shaped pupil apodization (black indicates opaque, white indicates clear). At center, the corresponding "bowtie" image plane mask. This "Ripple 3" design achieved 2.4e-9 contrast in 10% bandwidth averaged over the 4-10 lambda/D dark field (outlined) on the HCIT.

(Belikov *et al.*, 2007)

Vortex phase mask experiments on the HCIT

- *Vector vortex phase mask coronagraph offers high theoretical thoughput.*
- *Promising technology for the vortex mask is the liquid crystal polymer developed by JDSU (Mawet et al. 2007).*
- *A trial mask of this type, with topological charge 4, tuned for monochromatic 0.8 micron light, has been delivered to JPL for HCIT evaluations.*
- *Vortex mask can be achromatized to 10-20% bandwidths using three polymer layers, as for commercial achromatic half-wave plates, and this construction will be attempted this year.*

First vortex phase mask for the HCIT



- JDSU vortex mask with topological charge 4, delivered to JPL in December 2008
- Figure shows mask intensity transmittance as seen through crossed polarizers
- Central circular opaque dot masks the confusion zone at the central singularity

Summary

- *The ACCESS study will consider the relative merits and readiness of four major coronagraph types, as well as hybrid combinations*
- *The ACCESS science program will be defined in detail in terms of the predicted performance of a TRL6+ mission concept.*
- *The study will also identify specific areas of technology development that would advance the readiness of the major coronagraph types in the coming 5 years.*

End